14 April 97

POC: CNIE
1725 K Street N.W.
Suite 212
Washington, DC 20006

NLE
Committee for the National Institute for the Environment
1725 K St., NW, Suite 212, Washington, DC 20006 . . . . (202) 530-5810

CRS

Congressional Research Service
Issue Brief

91039: Magnetic Fusion: The DOE Fusion Energy Sciences Program

Updated January 24, 1997

Richard E. Rowberg
Science Policy Research Division

CONTENTS

SUMMARY

For over 40 years, the U.S. has been trying to harness the energy source of the hydrogen bomb to produce electricity. Controlling fusion, the nuclear reaction that powers the sun, requires confining and

produce electricity. Controlling fusion, the nuclear reaction that powers the sun, requires confining and heating deuterium and tritium nuclei to the point where they will collide (a D-T reaction) producing nuclear energy in a sustained, regulated way. One path to this goal, called magnetic fusion energy (MFE), is to use very strong magnetic fields to confine a deuterium and tritium plasma while heating it to fusion temperatures.

The potential benefits from fusion are enormous. The fuel resources are vast. Radioactive waste would be generated from a D-T reaction, but the long-term buildup would be orders of magnitude less than that of a comparable fission reactor.

There have been several experimental fusion devices, the most successful of which is known as the Tokamak (a Russian acronym). Experiments on one in Europe, called JET, and, recently, on a U.S. tokamak called TFTR, have produced substantial amounts of fusion power using D-T reactions. The next major milestone is to operate at significant power gain, that is, more fusion power produced than heating power used, and to develop the technology for a fusion power reactor. A conceptual design for such a device has been completed by an international consortium of the U.S., the European Union, Japan, and Russia. This machine, the International Thermonuclear Experimental Reactor (ITER), could be operating by about 2005. An agreement between the four partners for a $1 billion. 6-year ITER engineering design activity (EDA) was signed in July 1992, and is 2 years from completion. For FY1996, Congress appropriated $244 million, a 34% reduction from FY1995, and instructed DOE to develop a new program strategy emphasizing science research. In addition, Congress directed DOE to "integrate" its plans with the international fusion community. At DOE's request, the Fusion Energy Sciences Advisory Committee (FESAC, formerly FEAC) prepared a report with recommendations on restructuring its fusion program. That report recommended that DOE concentrate on the basic science and technology underlying the path to fusion power. While recommending continued participation in the ITER project, the report found that if the U.S. magnetic fusion budget were to drop below $250 million, such participation should be reconsidered. Finally, FEAC concluded that leadership in magnetic fusion research will pass to Japan and the European Union.

DOE restructured the program (renamed Fusion Energy Sciences (FES)) and adopted a new set of goals emphasizing basic science and technology. The FY1997 request is $255 million including $55 million for ITER. The Congress appropriated $232.5 million for FY1997 **including** funds for program direction and computer support - $16 million -- placed elsewhere in the DOE budget request, and specified continued participation in the ITER engineering design activity. DOE argues that the 14% decrease will slow program restructuring. Meanwhile, recent calculations indicate that the current ITER design may not be able to reach its goal of a self sustained fusion reaction and substantial power output. Many fusion scientists, however, claim that other models show more optimistic results, and point out the large body of semi- empirical evidence supporting the current design.

MOST RECENT DEVELOPMENTS

The DOE is completing re-orientation of its magnetic fusion research effort as directed by Congress. The new program, called the Fusion Energy Science Program, is focusing on fusion science and technology research. For FY1997, DOE requested $255 million, including $55 million for the ITER program. Congress appropriated $232.5 million including funds for two items -- program direction and computational support -- which were contained in other parts of the DOE request ($16 million was requested for these items). At the recommendation of FESAC, DOE recently announced a re- allocation of those funds putting more emphasis on fusion science, and reducing funds for fusion technology. A result of these actions will be the shutting down of the largest U.S. fusion research facility, the tokamak fusion test reactor at Princeton, in March, 1997. Concerning ITER, Germany and France each announced it would not seek to host its construction should it happen, citing the expected high cost of the machine. The European Commission Fusion Evaluation Board, however, recommended that Europe should try to be the host of the project if built. Recent calculations cast some doubt on whether the current ITER design will be capable of reaching the goal of a sustained fusion reaction. Many in the fusion research community are skeptical of these results, although most consider them a serious concern requiring further experiments. Finally, Japanese researchers claim to have reached the equivalent of

requiring further experiments. Finally, Japanese researchers claim to have reached the equivalent of break-even on its large tokamak device, the JT-60U.

BACKGROUND AND ANALYSIS

Fusion (http://wwwofe.er.doe.gov/More_HTML/more_fusion.html) is the fundamental mechanism in the universe for producing energy. It is the nuclear reaction which powers the stars. It is also a major contributor to the explosive power in the hydrogen bomb. Controlling this energy source to produce electricity has been sought since before the first hydrogen bomb was exploded. The potential benefits of controlled fusion are great. Successful development of a fusion power plant, however, is proving to be one of the most difficult scientific and technological challenges ever taken on. While progress has been steady, it may be at least 35 to 50 years before an operating power plant is built.

Fusion is one of a class of nuclear reactions. Another is fission, which involves the splitting of large nuclei, such as uranium, into smaller elements. Fission is the energy source of the atomic bomb, the first nuclear weapon built, and of nuclear power plants currently operating in the world. Such plants have been operating for about 30 years.

Fundamentals of Fusion

Fusion occurs when the nuclei (or core) of light atoms, such as isotopes (or forms) of the element hydrogen (deuterium and tritium), collide with sufficient energy to overcome the natural repulsive forces that exist between such nuclei. When this collision takes place, a D-T reaction is said to have occurred. If the two nuclei fuse, a heavier element -- a form of helium -- is created, along with a large quantity of energy. In order for the fusion reaction to take place, the nuclei must be heated to a very high temperature. In a hydrogen bomb, this is done by exploding a fission bomb -- uranium or plutonium -- forcing the deuterium and tritium together in a violent manner.

Fusion reactions are possible between a number of light atoms, including deuterium alone (a D-D reaction); deuterium and helium-3, an isotope of the element helium (a D- 3He reaction); and hydrogen and the element lithium, a light metal. All of these reactions occur much less frequently at a given temperature than the D-T reaction. For instance, the fusion energy produced from D-T reactions in a mixture of deuterium and tritium will be about 300 times greater than that from D-D reactions in a mixture of deuterium alone if both mixtures are heated to the same temperature and have the same density. For this reason, research into controlled fusion has concentrated on developing deuterium-tritium fueled reactors.

Potential Benefits of Magnetic Fusion Energy

Fuel Resources

The potential benefits of controlled fusion are many. Foremost is that in principle the fuel for such a plant is essentially inexhaustible. One out of every 6,670 water molecules contains deuterium rather than hydrogen, and there are no significant technical barriers to extracting deuterium from water. Tritium, however, does not occur in nature. It can be produced from the element lithium, which is also very abundant, although much less so than deuterium. To achieve the full resource potential of fusion will require reaching the conditions of plasma density, temperature and confinement time needed for energy production from reactions involving deuterium alone. As described below, these conditions are much more harder to reach than for deuterium and tritium which has proved difficult enough. The fusion research community, however, notes that even if success is reached with the D-T reaction, research will need to continue to reach power production from the D-D reaction.

Environmental and Safety Considerations

There also could be important environmental benefits from fusion. First, a controlled fusion power plant

There also could be important environmental benefits from fusion. First, a controlled fusion power plant would be inherently safe. A reaction that became "uncontrolled" in such a plant would extinguish itself almost instantly with no part of the system melting and with no significant release of radioactive material. Even major accidents that could occur, such as to the structure of a fusion powerplant would not result in any radiation release. Of course, such an accident could result in significant cost to the extent that the reactor was damaged.

A second environmental benefit is that the radioactive waste products produced in a fusion plant would be far less of a problem than those produced in a fission plant. Because of the nature of controlled fusion, it would be possible to reduce the long-term buildup of radioactive waste products by up to a million times below that of a fission system of comparable size while the quantity of radioactive material produced in a power plant of a given size may be comparable for the two types of reactions (at least for the first generation, deuterium-tritium fusion plants), the half-life of the radioactive products from such a fusion plant would be on the order of 100 years or less, compared to tens of thousands of years for those from a fission plant. Radioactive products from fusion plants, therefore, would decay much faster than those from fission plants, resulting in the large differences cited above. More advanced fusion systems using fuel combinations which produce few or no neutrons, such as the D-3He reaction, would result in substantially smaller amounts of radioactive products.

Paths to Fusion Energy Production

Two paths are being taken in attempts to attain controlled fusion. The first is to confine the light nuclei by a magnetic field and to heat them with an external source of electromagnetic energy. In this case, the deuterium and tritium are in a gas-like condition called a plasma. This process is called magnetic fusion energy (MFE). The other path is to heat very small clusters of solid deuterium and tritium by compressing these clusters with lasers or beams of particles. Such a process is called inertial confinement fusion (ICF) and simulates -- on a very small scale -- the actions of a hydrogen bomb. Once the reaction starts in either case, it is possible in principle for the heat generated by the fusion reactions to be sufficient to cause other light nuclei to collide, thereby sustaining the reaction without an external energy source. Such a condition, called ignition, has not yet been reached in practice. While substantial progress has been made over the last several years in both ICF and MFE, even the less stringent condition of break-even -- the point where power produced by the fusion reactions equals the power supplied by the external energy source -- is still to be achieved. A fusion power plant would operate between break-even and ignition. The ratio of power out to heating power supplied for an operating plant would be significantly greater than at break-even, but some external energy would still be supplied in order to control the reaction rate.

By way of comparison, stars operate by using their enormous gravitational force to confine the colliding nuclei. Enough heat is generated by the fusion reactions to force other nuclei to collide and undergo fusion so the reaction is sustained. Because of the large gravitational forces, these nuclei are unable to escape the stellar region before they gain the necessary energy to fuse with one another.

Achieving break-even and power amplification would be only the first steps in the process of producing useful power. The energy from the nuclear reactions would have to be converted into another form that could be used to do work. Energy is carried away from the fusion reactions in the form of neutrons moving at high speed. Because neutrons do not have an electrical charge, they are not confined by the magnetic field and will leave the plasma region. The neutrons will give their energy up if they collide with atoms of another material, causing that substance to heat. A prime candidate for this material for future fusion power plants is the liquid metal lithium. Lithium that is heated by colliding neutrons could then transfer that heat to water, producing steam. The steam, in turn, would drive a steam turbine and generator, producing electricity. While there are no fundamental scientific barriers to this process, putting it into practice will be a complicated engineering task requiring substantial development. A second reason for using lithium is that reaction between the lithium atoms and the neutrons would produce the tritium necessary for the reactor fuel.

Magnetic Fusion Energy Research

Both the magnetic fusion energy (MFE) and inertial confinement fusion (ICF) research activities are

Both the magnetic fusion energy (MFE) and inertial confinement fusion (ICF) research activities are funded by the U.S. Department of Energy (http://www.doe.gov). The ICF program currently is primarily oriented to defense applications, for simulation of nuclear weapons, although energy applications are an important part of the research effort. Nearly all of the funds for ICF research come from DOE's Defense Programs (http://www.dp.doe.gov). An major initiative of the DOE ICF program is the National Ignition Facility (NIF) (http://www- lasers.llnl.gov/lasers/nif.html) at DOE's Lawrence Livermore National Laboratory which is currently entering the detailed engineering design stage. While the NIF is primarily for weapons applications, it will also carry out important research for potential energy production from inertial fusion.

Magnetic fusion energy research is within DOE's civilian programs and is located in the Office of Energy Research. While funding for ICF research now exceeds that for

TABLE or GRAPHIC not shown here

magnetic fusion, the latter has been and continues to be the major fusion energy focus in the United States. The remainder of this issue brief is on magnetic fusion.

Developments to Date

Magnetic fusion energy research has been underway for over 40 years. The scientific challenges are to develop ways to confine a high-density deuterium and tritium plasma and to heat it so that the combination of temperature, density, and confinement time are sufficient that break-even and beyond are reached. Much progress has been made in the last 20 years in meeting these scientific challenges. Since the mid- 1970s, the amount of measurable fusion power produced in fusion experiments has increased by a factor of over fifty million, or seven orders of magnitude. **Figure 1** shows the increase in fusion power produced from large experimental devices since from 1978 to 1994. The solid squares represent achieved values while the 4xxendz

TABLE or GRAPHIC not shown here

open squares represent targets for future experiments. The symbol TFTR, JET and ITER are described on the next page.

These achieved and projected power levels have or will take place on tokamak devices. The tokamak (a Russian acronym) concept was first demonstrated in the former Soviet Union in 1968. It is a device in which the plasma is contained in a toroidal (donut-shaped) chamber surrounded by magnetic field coils.(See **Figure 2**). The plasma produces a large electric current by circulating within the chamber, and the combination of the magnetic field produced by that current and by the coils imparts a high degree of stability to the plasma. This stability has made possible much longer confinement times than previous devices. Currently, the largest and most successful tokamaks are the tokamak fusion test reactor (TFTR) at Princeton Plasma Physics Laboratory (http://www.pppl.gov) and the Joint European Torus (JET) (http://www.jet.uk) which is located in Great Britain and is funded by the European Union. There are many other tokamaks operating in the world today in Japan, Italy and France, and, in the United States, at General Atomics (http://fusioned.gat.com) in San Diego and MIT.

On November 10, 1991, researchers at JET produced about 1.8 million watts (MW) of fusion power using a mixture of deuterium and tritium (D-T) to form the plasma. The TFTR at Princeton began experiments using deuterium and tritium in late November 1993. In September 1994, the TFTR produced 10.7 MW of fusion power (see TFTR symbol in Figure 1). A ratio of power produced to power used to heat the plasma, called Q, of about 0.3 was reached. In addition, there was evidence of enhanced confinement of the plasma during the heating pulse and some indications of heating of the plasma by alpha particles, products of the reaction between deuterium and tritium. It appears that plasma behavior is improved by the addition of tritium. Many in the fusion research community believe these experiments demonstrate conclusively the scientific feasibility of controlled fusion. In Japan, a large tokamak called the JT-60U (http://www-jt60.naka.jaeri.go.jp), recently reported reaching conditions in a deuterium only plasma which would be equivalent to break-even conditions, Q=1.05, in a plasma of 50% tritium and 50% deuterium.

A value of 20,000 kw is expected to be reached on JET within the next few years (see the JET symbol in Figure 1). By way of comparison, the design power output of the International Thermonuclear Experimental Reactor (ITER) (http://iter.ucsd.edu), whose plasma would be about three times as large as that of the TFTR, would be (see below for more on ITER), is 1,500,000 kw (see the ITER symbol in Figure 1).

In a recent development which offers great promise for an eventual fusion power reactor, researchers at both Princeton and General Atomics in San Diego have been able to greatly enhance plasma confinement in their respective tokamak devices. In addition, the loss of heat from the plasma has been reduced by over a factor of 40 and the peak density of the plasma increased over three times. The process used has been explored in the past, but only to a limited extent. These new experiments expanded the region in the plasma over which the process was in effect. Scientists at Princeton now say that they will be able to achieve fusion power production of up to 40 MW in the TFTR, when using a D-T mixture, which will allow significant heating of the plasma by the fusion reactions. A preliminary prediction by some fusion researchers is that these developments could reduce the size and cost of an eventual fusion reactor based on the tokamak concept by about 50%.

Future Developments

The ultimate goal of the worldwide effort in controlled fusion research is to development of useful energy -- most likely electricity -- from a fusion powered reactor. To help reach this goal, the major players in the international fusion research effort -- the United States, Japan, Russia, and the European Union -- are participating jointly in the engineering design of the largest international science project to date, the International Thermonuclear Experimental Reactor (ITER). The project's ultimate objective is to demonstrate extended operation of a fusion plasma after substantial power amplification has been achieved. It will also be an engineering test bed for those systems needed on an operating power plant. The first phase of this project, completed in December 1990, yielding the conceptual design of a reactor proposal estimated to cost $4.9 billion which could be completed by 2005 and operated for about 15 years. A more recent cost estimate of $8 million was made in December 1995 on the basis of an interim design approved by the ITER governing council. The current phase is the development of a detailed engineering design. This phase, which began in 1992 and which is called the Engineering Design Activity (EDA), is scheduled to for completion in 1998 at a cost of about $1 billion, shared by the four partners. The decision whether and, if so, where to construct ITER has not yet been made.

If the ITER project were to be completed, the final stage of the magnetic fusion energy effort would be the construction and operation of a demonstration power plant that would produce electric power. A 1990 report by the Fusion Policy Advisory Committee (FPAC) of the United States Department of Energy (DOE) stated that such a plant could be completed and running by 2025 provided sufficient research support were available to that time.

Congressional Considerations

Department of Energy Research Program

TABLE or GRAPHIC not shown here

The Nation's magnetic fusion energy (MFE) research program began in 1951 under the auspices of the former United States Atomic Energy Commission. Since that time, the United States has spent over $13.3 billion, in constant 1994 dollars, on research into MFE. **Figure 3** shows the budget history since 1960 in constant 1994 dollars. In FY1996, the Congress approved $244 million, $122 million below the DOE request. After internal DOE adjustments, including a shift of $9.0 million for program direction to the Office of Energy Research and additional funds for the program's contribution to the National Energy Research Computer Center, the program's FY1996 operating budget was $227.4 million. The MFE appropriation for FY1996, and the

TABLE or GRAPHIC not shown here

FY1997 request and appropriation are shown in **Table 1**. The FY1997 action will be discussed in more detail below. The breakdown according to these new activities is shown in the table. Under **fusion and plasma sciences**, DOE is funding three large tokamak efforts -- the TFTR at Princeton, the DIII-D at General Atomics in San Diego, and the Alcator C-Mod at the Massachusetts of Technology. Funding for alternate concepts research also falls within this activity. Support for the ITER engineering design activity (EDA) falls within **fusion technology**.

The FY1997 budget request reflected a major re-structuring of the of the MFE (now Fusion Energy Sciences, FES (http://wwwofe.er.doe.gov)) research program brought on by the 34% budget reduction it received for FY1996 and the instructions of Congress accompanying that appropriation. A draft plan for the restructured program was prepared by DOE, and DOE asked the Fusion Energy Advisory Council (FEAC) to prepare a set of recommendations for the future of the program based on its review of the DOE proposal and congressional direction. Congress instructed DOE to restructure its "strategy, content and near-to-medium-term objectives" since increased funding for the program was unlikely for the next several years at least. The Congress directed that the program "should emphasize continued development of fusion science, increased attention to concept improvement and alternative approaches to fusion, and development and testing of the low-activation structural materials so important for fusion's attractiveness as an energy source."

The FEAC issued its report, "A Restructured Fusion Energy Sciences Program" (http://wwwofe.er.doe.gov/More_HTML/FusionDocs.html) on January 27, 1996. The FEAC report recommended that the fusion program be modified to be in concert with the instructions from Congress accompanying the FY1996 appropriations, and should include continued participation in the ITER engineering design activity (EDA). In response to the FEAC report, DOE made a number of changes in the magnetic fusion program reflected in its FY1997 budget submission. The program's name changed to Fusion Energy Sciences and the program changed its emphasis from energy technology development to basic plasma and fusion science. The Department also announced that it would increase its efforts on alternate concepts. Finally, DOE stated that it would continue to participate in the ITER EDA.

Three additional studies were carried out by the Fusion Energy Sciences Advisory Committee(FESAC)(http://wwwofe.er.doe.gov/More_HTML/FESAC_CHARG ES_Reports)(the name of the Fusion Energy Advisory Council was also changed to the Fusion Energy Sciences Advisory Council) to help implement the program's re-structuring. First, FESAC reviewed the three major facilities, currently funded by the FES program, and their revised research plans. The facilities reviewed were the TFTR, the DIII-D, and the Alcator C-Mod at MIT. Second, FESAC reviewed the current status of alternate concept development to recommend "an investment strategy for funding alternative concepts." The third study reviewed inertial fusion energy research in order to provide DOE with guidance.

These reports were reviewed at a meeting of FESAC held on July 16-18, 1996. The recommendations of FESAC are now being prepared and will be delivered to DOE for its consideration. The reports assumed a budget of at least $250 million for FY1997. Since that meeting, DOE issued a "Strategic Plan for the Restructured U.S. Fusion Energy Sciences Program" in August 1996.

In the meantime, Congress completed final action of the FY1997 appropriation. A total of $232.5 million was appropriated including funds for program direction and for the FES contribution to the National Energy Research Computer Center. (DOE estimates that the appropriation will be $230.1 million after accounting for a general reduction in DOE funds.) The DOE had requested $16 million for these two items, but included them in other accounts, not within the FES account. As a result, the FY1997 appropriation represents a net reduction of about 14% from the request and of 6% from the FY1996 appropriation. Language in the Conference report permitted DOE to allocate the funds to the extent possible although the House and Senate reports each recommended $55 million the continuing U.S. contribution to the ITER EDA project.

At a meeting of FESAC in September 1996, DOE presented its proposal for allocating the FY1997 appropriation which is shown in **Table 1**. At the meeting, FESAC considered a number of recommendations for changes in the allocations and presented its advice to DOE in letter dated October

recommendations for changes in the allocations and presented its advice to DOE in letter dated October 3, 1996. In the letter FESAC offered its general support for the DOE proposal. The committee repeated its view of "the importance of proceeding expeditiously to implement the restructured program defined by FEAC." The FESAC stated, however, that "the fusion community needs to do further work on refining the vision and long-term goals of the program ...".

At the Fusion Strategic Planning Workshop held on October 22, 1996, DOE presented its response to the recommendations offered by FESAC. In total, DOE re-allocated $4.5 million putting more resources into inertial fusion energy, technology and materials, theory and modeling, and systems studies at the expense of tokamak research physics. These are summarized in **Table 1.** At the workshop, DOE also reviewed its response to the FEAC report of January 1996. The DOE stated that it has shifted the magnetic fusion research focus to innovation and science. Further, DOE pointed out that once TFTR research is ended in FY1997, additional funds should be available to pursue additional fusion science research. Finally, DOE reaffirmed its commitment to the ITER EDA at a constant level of funding.

Program Issues

The U.S. magnetic fusion energy R&D program is in the most critical period of its long history and is undergoing a major re-orientation. Even before the Congress reduced its budget, it was clear that funds required to meet the old MFE program's goals over the next 5 to 7 years could not be provided by DOE. With the knowledge of this fact and in anticipation of congressional budget cuts, the Office of Science and Technology Policy (OSTP) (http://www.whitehouse.gov/OSTP.html) asked the Presidential Commission on Science and Technology (PCAST) to review the entire magnetic fusion research program, and to come up with recommendations for its future. The recommendations of that study centered on a budget of $320 million for FY1996. Once the Congress had acted on the budget, however, a new strategy had to be drawn up for the program as described above. Appropriation actions so far for FY1997 indicate that further changes will be needed. Before discussing the issues raised by the program's restructuring, however, it is useful to examine briefly the program's recent history.

In September 1990, the DOE Fusion Policy Advisory Committee (FPAC) released a report presenting a "conceptual program" for the United States to build an "operating demonstration [fusion] power plant by 2025 and at least one operating commercial power plant by 2040." To do this, the Committee suggested a budget path for the United States program that would increase to about $600 million by FY1996 (expressed in constant FY1990 dollars -- in FY1995 dollars, the amount would be $730 million). The Committee also devised a more constrained path -- at the request of then-DOE Secretary Watkins -- that would move to $470 million (about $570 million in FY1995 dollars) by that time. The Committee stated that its goals could only be reached by the constrained path if significant foreign contributions to major components of the recommended United States program could be obtained.

DOE adopted the FPAC goals for the FY1992 budget request. In that request, DOE stated that it would begin the transition of the magnetic fusion energy program from a research orientation to one which emphasizes technology development. The specific objective was an operating demonstration power plant by 2025.

To assist in guiding the program in accordance with the FPAC recommendations, DOE set up the Fusion Energy Advisory Committee (FEAC). In a report issued on Oct. 23, 1992, the FEAC recommended that highest priority be given to "strong U.S. participation in the ITER Engineering Design Activity" and an early start to D-T experiments on TFTR to be completed by the end of FY1994. To achieve these goals, FEAC concluded that the MFE budget would have to have real growth of 5% per year for the period 1993 to 2000. The FEAC also argued that if budgets were to decline in real terms, the U.S. fusion program would have to undergo a "serious re-examination."

The major consequence of DOE's actions in the early 1990s was that the budget requirements for the MFE program to meet all its goals had risen substantially by the time the 104th Congress began. While DOE did not issue any estimates, the PCAST report mentioned above said that an increase to $860 million by FY2002 with average funding of $645 million between FY1995 and FY2005 could be justified. Even before the 104th Congress was elected, however, it was clear that these increases were very unlikely and that even a declining budget was possible. Once the new Congress begin to address the

very unlikely and that even a declining budget was possible. Once the new Congress begin to address the fusion research budget, it was clear that large declines would occur.

The MFE program entered FY1996 with a major international commitment, a set of goals which would require substantial budget growth, and an appropriation from Congress reducing its budget by 34% and promising no budget increases for several years. In response to the budget cuts, DOE has made substantial reductions in the magnetic fusion research effort. On September 25, 1995, DOE announced that 246 staff would be laid off at the Princeton Plasma Physics Lab. Other layoffs have also occurred. While none of the three major tokamaks thus far is scheduled to be shut down, each has been operating at a reduced schedule compared to FY1995. Other, smaller tokamaks have been shut down. Because of the cutbacks and shutdowns, a significant portion of the FY1996 budget is being used for closeout costs.

The DOE also undertook the development of a new program strategy, as described above, in response to the budget cuts and specific instructions from Congress. That new strategy became part of the FY1997 budget request. In the reports accompanying the FY1997 appropriations recommendation, both the Senate and House Appropriations Committees noted their approval of the DOE restructuring activity. There remain, however, a number of issues about the program's future, accentuated by the fact that the DOE FES program received an FY1997 appropriation $14 million below the FY1996 level. Three of particular concern are the involvement in the international fusion research effort, the program's overall focus, and its concentration on the tokamak as the option of choice for a fusion reactor.

The magnetic fusion research program has had a significant international flavor since its inception in the early 1950s. In addition to the United States, Japan, the European Union and Russia have had large fusion research programs over the past few decades. Furthermore, there has been substantial cooperation between these countries over that period. The ITER project is in one sense the culmination of this international cooperation. The new strategy and budget for the FES program will dramatically alter the U.S. contribution to the international effort. For this fiscal year, Japan is spending $500 million of magnetic fusion research while the European Union is spending $600 million, and leadership in fusion research has transferred to them. Given this fact, the primary question for the United States is how it can make the most effective contribution to the international effort.

International cooperation in fusion research is currently dominated by the ITER Engineering Design Activity (EDA). Despite the long history of international cooperation, arrangements for the EDA -- the second phase of the ITER program -- proved very difficult and resulted in a complex arrangement. The EDA has been underway since 1992 and is scheduled for completion in 1998. Total cost of the EDA is estimated to be $1 billion. Currently, no construction decision on ITER has been made. The projected multi-billion construction cost of the machine means that contributions from the major partners would have to be in the billion dollar plus range, with the host making the major contribution. Recent decisions by some of the partner countries about hosting the project have changed its prospects as discussed below.

While continued participation in ITER, at least through the engineering design phase, was part of the FY1997 FES budget request and the congressional appropriation, some in the fusion research community question that commitment given the current budget situation. The direct DOE contribution to the ITER EDA for FY1996 is $55 million, 22.5% of the entire program budget. For FY1997, DOE again provide $55 million for the EDA which is now 23.9% of the total FES appropriation. Those who urge DOE to withdraw from ITER argue that a strong domestic core program is not sustainable under these conditions. They state that there is much basic science that can and should be done on fusion plasmas before deciding on a direction for a fusion power plant. A recent report by the National Research Council points out many other potential applications which could be achieved by additional research in plasma physics. Exiting the ITER EDA activity, however, could result in a number of important negative consequences. If the rest of the world fusion community continues with ITER and constructs such a device without the United States, the United States could be in a severe economic disadvantage if this path toward fusion power proves technically and economically successful. In the shorter term, if the United States did not participate in the ITER EDA, the nation probably would lose access to the technological advances being made in the EDA. Currently, DOE estimates a return of three to four times on our investment in ITER. Finally, withdrawal from our commitments in the ITER program may jeopardize other international agreements.

The future of ITER, however, contains its own uncertainties regardless of what the U.S. does. Both Germany and France recently announced that they were no longer interested in being considered the host of ITER construction should it take place. They cited the expected high cost of the machine and the high contribution that the host country would have to make as the main reason for withdrawing from consideration. Both, however, stated that they will fulfill their commitments to the EDA but said nothing about whether they would support construction even if another country -- probably Japan -- agreed to be the host site. Clearly the withdrawal of the U.S., Germany, and France from consideration as the host reduces the likelihood of a decision to go forward with construction.

In addition, recent scientific findings have cast doubt on whether the current design of ITER would achieve its goal a self sustained fusion reaction (ignition) and produce substantially more power than is used to heat the plasma to fusion conditions. Two researchers at the Institute for Fusion Studies (http://w3fusion.ph.utexas.edu/ifs/) at the University of Texas at Austin, have developed a theoretical model which suggest that the ITER plasma would become so turbulent that it would lose heat at a rate sufficient to keep it from reaching ignition. In addition, these two scientists reviewed the research carried out by ITER staff and concluded that the extrapolations they made to predict ITER performance may be in error.

Although most fusion researchers believe the work done by the Texas researchers to be of high quality and worth serious consideration, they are not yet ready to concede that the current ITER design is seriously flawed. They point out that the ITER is necessarily an experimental device and its design is based in a large degree on semi- empirical extrapolation from existing experimental data. These extrapolations, the ITER supporters point out, have consistently indicated that ITER would perform as expected. The Texas work represents a step in the direction of a more fundamental model of ITER physics, but which still partly depends on empirical factors. Other fusion scientists also point out that other, similar models predict more optimistic behavior for ITER. There is clear agreement, however, that additional work is needed to resolve this issue including some experiments which can be carried out on existing tokamaks. In addition, others have proposed possible solutions to reduce the amount of turbulence that could occur in the ITER plasma. One potential solution will be tested on the TFTR at Princeton until that machine is shut down in March, 1997.

At this time, DOE is planning to fulfill its commitment to the ITER EDA, although its contribution will be less than originally anticipated. In addition, the Congress also seems intent on ensuring that our obligation to the international agreement is met. While the full House enactment and recommendation being considered by the Senate will likely increase calls for a sharp drop, if not complete withdrawal, in the U.S. contribution, that is not likely to happen for the remainder of the EDA. If and when a decision to construct ITER is made, however, the debate about whether the U.S. should continue its contribution is likely to be much more contentious even if such contributions are on the order of $50 million per year.

Another issue concerns the program's focus on the tokamak concept. The success of the tokamak over the last 20 years has elevated it to the role of leading contender for a demonstration power reactor (DEMO). Indeed, the attainment of such a DEMO was the goal of the U.S. program until this year. Despite the recent results described above, a long history of experimental results on tokamak devices still leads most fusion researchers to believe that a tokamak-like device is the most promising path to controlled fusion. It is this belief that underpins the decision to proceed with ITER.

There are those in the fusion community, however, who believe that the tokamak path is not the one to follow. While conceding the scientific success of the tokamak, these critics argue that the concept is inherently too complicated to result in an affordable and reliable power reactor candidate, and may not work at the scale needed for a power plant. The recent calculations about the potential difficulties of the ITER design are likely to add to these concerns. Furthermore, these critics point out that any tokamak powerplant is most likely to be confined to using a deuterium-tritium mixture, resulting in copious quantities of neutrons and substantial buildup of radioactive materials. While, as discussed above, this buildup would contain no long lived materials analogous to the plutonium production from a fission reactor, the critics argue that the quantity of radioactive materials which would need disposal would greatly add to the cost and complexity of the reactor.

As a result of these concerns, several in the fusion research community argue for a greatly expanded research effort in alternate concepts. This effort would focus on basic science, for the most part, in order to help determine which candidates appear most promising for further development. Several possibilities exist, including other magnetic confinement schemes, inertial confinement systems, and concepts which propose to use electrostatic confinement or circulating beams. In recent testimony before the Subcommittee on Energy and Environment of the House Science Committee, L. John Perkins of DOE's Lawrence Livermore Laboratory listed 19 such possibilities. He also argued that DOE should increase funding of alternatives within the FES program to 25%-30% of the budget. He, along with others supporting an increased effort toward alternatives, emphasize that DOE should only continue with those concepts which have the hope of significantly improving upon the tokamak concept in terms of being environmentally and economically acceptable reactor candidates.

Partly in response to that urging, DOE has stated that it will expand its research support for alternatives. Prior to this year, DOE's support of alternate concept research amounted to about 4% of its fusion budget. Most of this was for inertial fusion energy research. For FY1997, DOE is planning to increase alternate concepts funding to about 6% based in large part on the recommendations of the FESAC report described above. The FY1997 amount includes $5 million for startup of the national spherical tokamak experiment. Despite this increase, the likely appropriations for future years may mean, however, that development of the alternate concepts research strategy will be slower than some critics would like.

For the foreseeable future, however, the dominant portion of FES research funding will continue to go to research on tokamaks. The major facilities report of FESAC argues that much good fusion science remains to be done on the three large tokamak facilities currently supported by DOE. The final appropriation for the FY1997, however, requires that such support will have to be reduced. In particular, operation of the TFTR will not be extended past its scheduled close down in March, 1997.

A related issue is the general focus of the program. As a result of recommendations of DOE's magnetic fusion advisory committees in the early 1990s (see above), the principal goal of the MFE program has been the development of a demonstration power reactor. While it continued to fund basic research in plasma physics, that function became a decreasing portion of the program and that research was primarily in support of the main goals. While there was some concern about this direction, it received the support of DOE and Congress until FY1996. The DOE magnetic fusion program was a development more than a research program.

It became clear early in 1995 that DOE was not going to receive the funds required to pursue this development goal as laid out by the advisory committees. The first response to the changing budget environment was the PCAST study mentioned above. Its report set out a path for DOE to follow at a budget of $320 million for FY1996. The PCAST recommendations emphasized an international approach where the United States would try to expand the number of projects which had international collaborators. In addition, PCAST urged that DOE re-negotiate the ITER project to a scaled-down machine, approximately one-third the size of the current design. The overall goal, however, would remain development.

The budget and instructions finally approved by Congress for FY1996 caused DOE to abandon the development path in favor of one which emphasizes fusion and plasma science. There are those, however, who believe that DOE needs to go farther in this direction. They argue that portion of the budget for plasma science should be an even higher fraction than recommended by FESAC, and that the continued emphasis on tokamaks, including the ITER contribution, is not the dramatic departure from the development path that is needed. While much of FES program will still be on the tokamak, including ITER, it will emphasize greater scientific understanding of tokamak physics. As the new program unfolds the extent of the shift will become clearer.

The reduction in the program's FY1997 appropriations from FY1996 (about 4.7%) has raised concern about how effectively DOE can proceed with its restructuring. While both the full House and the Senate Appropriations Committees in report language expressed approval of the way DOE is proceeding, both DOE and FESAC believe the level approved by Congress will slow restructuring progress. Specifically, DOE stated that the FY1997 appropriation "will slow implementation of the restructured program."They

DOE stated that the FY1997 appropriation "will slow implementation of the restructured program." They argued that a budget level of at least $250 million was needed to continue important research on the large facilities while building efforts on basic plasma and fusion science and continuing to support the ITER EDA.

The actions of the Congress to date indicate that the nation is not yet ready to support magnetic fusion energy development to fruition. It appears that such efforts will be left to future generations, unless the current international efforts are successful with or without U.S. participation. Congressional direction to continue to participate in that international program appear, in part, to be predicated on that possibility. The consequences of these policy decisions remain to be seen. If and when the choice is made to proceed with fusion energy development, it is still likely to take decades and several billions of dollars to produce a fusion power plant. While the possibility of a major scientific and/or technological breakthrough which would greatly shorten the time and cost cannot be ruled out, enough is known about the science and technology of magnetic fusion to conclude that such is unlikely.

Congressional Actions

On March 7, 1996, a hearing on the magnetic fusion program was held before the Subcommittee on Energy and Environment of the House Science Committee. The findings of the FEAC report were presented and several witnesses commented on the report as well as other issues concerning the program. DOE testified and outlined the new strategy for the Fusion Energy Science program in response to the FEAC report.

On July 16, 1996, the House Appropriations Committee reported H.R. 3816, the Energy and Water Development Appropriations Act of 1997. The Senate Appropriations Committee reported S. 1959, its version of the Act, on the same day. The House committee recommendation was $225 million including $16 million for two items not contained within the original DOE FES request but elsewhere in the DOE budget. The Senate committee recommendation was $240 million including $14.7 million for those two items. Both actions recommended full funding for ITER. The House and Senate committee reports both commend the DOE restructuring effort but state that budget restraints will force it to move at a slower pace. Finally, the House report specifies on which projects and programs all but $16 million of the recommendation should be spent, while the Senate left those choices up to DOE.

On July 25, 1996, the House passed H.R. 3816 while the Senate passed S. 1959 on July 30, 1996. While on the House floor, the recommendation for the FES program was reduced by $1 million as a result of an across the board cut in Energy Supply R&D programs under the Committee's jurisdiction to help fund an increase in the renewable energy R&D program. No changes occurred during Senate floor action.

On September 11, 1996, a House-Senate Conference agreed to a funding level of $232.5 million including funds for program direction and computer support. The Conference report, however, left the amounts for these two items at DOE's discretion. On September 12, 1996, the full House agreed to this Conference action and the Senate concurred on September 17, 1996.

LEGISLATION

P.L. 104-46, H.R. 1905

Energy and Water Development Appropriations Act of 1996. Recommends $229.1 million for magnetic fusion energy research for FY1996. Reported by Committee on Appropriations, June 13, 1996 (H.Rept. 104-149). Passed House July 12, 1995 by a vote of 400 to 27. Reported to Senate by Committee on Appropriations (S.Rept. 104-120) July 27, 1995. Committee recommends appropriations of $225.1 million for FY1996. Passed Senate August 1, 1995, as amended, by voice vote. Amendment to allow DOE to use $56 million from general administrative savings for continued operation of the TFTR. House and Senate agreed to conference report (H.Rept. 104-293) recommending $244.1 million. Signed into law November 13, 1995.

P.L. 104-206, H.R. 3618 and S. 1959
Energy and Water Development Appropriations Act of 1997. Reported by Committee on Appropriations July 16, 1996 (H.Rept. 104-679). Recommends $225 million for fusion energy science research for FY1997. Passed House July 25, 1996 by a vote of 391-23. Reported as S. 1959 to Senate by Committee on Appropriations July 16, 1996 (S.Rept. 104-320). Recommends $240 million for fusion energy science research for FY1997. Substituted H.R. 3816 as an amendment and passed Senate July 30, 1996 by a vote of 93-6. House and Senate agreed to conference report (H.Rept. 104-782) recommending $232.5 million. Signed into law September 30, 1996.

FOR ADDITIONAL READING

Executive Office of the President. Office of Science and Technology Policy. The U.S. program of fusion energy research and development. Report of the Fusion Review Panel. The President's Committee of Advisors on Science and Technology (PCAST). Washington, D.C. July 1995.

Furth, H.P. Magnetic confinement fusion. Science, v. 249, Sept. 28, 1990: 1522-27.

International Atomic Energy Agency. ITER definition phase report. Vienna. November 1988.

National Research Council. Plasma science: from fundamental research to technological applications. National Academy Press. Washington, D.C. 1995.

U.S. Congress. Office of Technology Assessment. Starpower: The U.S. and the international quest for fusion energy. OTA-E-338. Washington, D.C. 1987.

-----The fusion energy program: The role of TPX and alternate concepts. OTA-BP-ETI- 141. Washington, D.C. 1995.

U.S. Department of Energy. Fiscal year 1997 congressional budget request, budget highlights. DOE/CR-0039. Washington, D.C. March 1996. p. 59.

-----Final Report of the Fusion Policy Advisory Committee. DOE/S-0081. Washington, D.C., September 1990.

-----A Restructured fusion energy sciences program. Advisory Report Submitted to Dr. Martha A. Krebs, Director, Office of Energy Research, U.S. DOE. Fusion Energy Advisory Committee. Washington, D.C. January 27, 1996.
